REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
12-12-2012

2. REPORT DATE
Final

3. DATES COVERED *(From - To)*
October 2010 -- September 2012

4. TITLE AND SUBTITLE
Expansion of a Direct Simulation-Based Study of Radiance in a Dynamic Ocean

5a. CONTRACT NUMBER

5b. GRANT NUMBER
N00014-11-1-0091

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Yue, Dick K.P. and Yuming Liu

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Massachusetts Institute of Technoloby
77 Mass Avenue
Cambridge, MA 02139

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
ONR, Code 322OB
875 North Randolph Street, Suite 1425
Arlington, VA 22203-1995

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The objective of the project is to apply advanced physics-based computational prediction capabilities, for oceanic radiative transfer, surface wave dynamics and near surface turbulence, to further understand the characteristics and obtain modeling parameterizations of underwater radiance in realistic ocean environments by making use of the field measurements obtained in the ONR RaDyO project. The focus of the research is on direct quantitative comparisons and cross validations and calibrations of the model predictions and the field measurements of surface wave features and underwater radiance properties.

15. SUBJECT TERMS
Ocean surface waves, ocean surface turbulence, underwater radiance prediction, Monte Carlo simulation of radiance transfer

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES
U	U	U	UU	4

19a. NAME OF RESPONSIBLE PERSON
Yue, Dick K.P.

19b. TELEPONE NUMBER (*Include area code)*
617-253-6823

Expansion of a Direct Simulation-Based Study of Radiance in a Dynamic Ocean

Dick K.P. Yue
Center for Ocean Engineering
Massachusetts Institute of Technology
Room 5-321, 77 Massachusetts Ave, Cambridge, MA 02139
phone: (617) 253-6823 fax: (617) 258-9389 email: yue@mit.edu

Yuming Liu
Center for Ocean Engineering
Massachusetts Institute of Technology
Room 5-326C, 77 Massachusetts Ave, Cambridge, MA 02139
phone: (617) 252-1647 fax: (617) 258-9389 email: yuming@mit.edu

Award Number: N00014-11-1-0091
http://www.mit.edu/~vfrl/research/Zao.html

LONG-TERM GOALS

The goal is to develop direct simulation/physics-based forward and inverse capabilities for radiance prediction in a dynamic ocean environment. The simulation-based model includes and integrates all of the relevant dynamical processes in the upper ocean surface boundary layer into a physics-based computational prediction capability for the time-dependent radiative transfer (RT).

OBJECTIVES

To develop physics-based modeling and computational prediction and inverse capability for the time-dependent underwater radiative transfer incorporating the dynamical processes on the ocean surface and the upper ocean surface boundary layer (SBL):

- Develop efficacious direct computational capabilities and analytical models to predict the radiative transfer (RT) process of solar radiation in the coupled atmosphere-ocean system; Obtain understanding, modeling and parameterizations of dependencies of oceanic radiance on the surface wave environment.
- Develop direct simulation approaches to predict large-scale realistic nonlinear ocean surface wave fields for RT modeling.
- Obtain quantitative validation and cross-calibrations with experimental field data.
- Investigate effects of dynamic ocean surface waves on in-water solar radiation patterns and statistics.
- Establish a preliminary framework for inverse sensing and reconstruction of ocean surface conditions based on underwater light field measurements.

APPROACH

We apply forward and backward Monte Carlo methods to simulate the radiative transfer in the coupled atmosphere-ocean system to investigate the spatial and temporal characteristics of the in-water radiance and irradiance fields. Both scalar and vector radiaitve transfer simulations are developed to consider the unpolarized and polarized light, respectively. All our programs are parallelized and optimized to run on modern high performance computing (HPC) platforms utilizing up to $O(10^3)$ processors. To obtain more realistic dynamic ocean surface conditions, we extend and apply an high-order spectral method and LES capabilities for nonlinear evolution of capillary and gravity waves as well as their interactions with wind and ocean turbulence (Xu et al 2012). A hybrid method combining Monte Carlo and ray-tracing is also developed to characterize the radiaitive transfer process in inhomogeneous medium, such as in strong ocean turbulence, particularly for those with a strong refractive index variation. More direct understanding of the short term in-water light variability is acquired by our new physics-based analytical model (we call GP) which is able to describe the probability density function (PDF) of the downwelling irradiance at the upper ocean (Shen et al 2011). This model takes into consideration the key factors affecting the statistics of downwelling irradiance, such as the ocean surface wave spectrum and the water IOPs. This model also provides an asymptotic expression for the probability of occurrence of extreme values.

WORK COMPLETED

- **Direct quantitative comparisons between ONR RaDyO field measurements and model prediction.** We performed quantitative comparisons by incorporating all the key RaDyO wave, IOPs and underwater radiance measurements with combined wavefield (reconstruction and prediction) and RT (full unpolarized and polarized light field) modeling and closed-form analytical formula.
- **Data assimilation and preliminary inverse modeling.** We developed a framework and obtained preliminary results for the inverse problem of deducing parameters associated with the dynamic ocean surface based on underwater light field characteristics. The immediate goal of the inversion problem is to use passively measured light field quantities including irradiance, radiance and polarization data in deterministic or statistic forms, to deduce ocean wavefield properties such as surface wind speed and direction, MSS, and wave frequency and directionality. Such inversion might be achieved utilizing explicit formulas derived from the analytical solutions of irradiance and radiance statistics or spectrum.

RESULTS

We developed a 3D Monte Carlo (MC) RT simulation capability for unpolarized and polarized light for the atmosphere-ocean system. The model is systematically validated by direct comparisons with existing theories and numerical model predictions and with field data including ONR RaDyo measurements. The developed 3D MC RT model was applied to investigate the characteristics of polarization distribution and underwater irradiance in various ocean surface environments.

(1) ***Validation of models by quantitative comparison with field data:*** We obtained model-to-model validations by comparing our simulation with the classic discrete-ordinate method and invariant imbedding method. We made extensive cross-calibrations of our simulation predictions with the field data obtained in RaDyO Santa Barbara Channel (SBC) and Hawaii experiments (see, for example, figure 1a *and* 1b, for polarized light data from Voss and IOPs data from Twardowski). Validations of the GP closed-form model for probability density function of downelling irradiance were made by comparing the experiments data obtained by Stramski et al and Monte Carlo simulations (figure 1c).

(2) ***Effects of ocean surface roughness and nonlinearity on underwater light fields:*** We characterized the dynamic ocean surface wavefield in terms of its roughness and nonlinearity. The roughness, which is usually characterized by the surface wind speed U_{10} or the mean square slope (MSS), has been long recognized as the key parameter affecting the underwater light field patterns and variability. However, quantitative and conclusive studies of its effects are not clear yet. For both unpolarized and polarized underwater light fields, we analyzed the effects of the random ocean surface waves in terms of the mean value and higher-order moments of time-series light measurements. Our modeling studies showed the pattern of the downwelling irradiance is not affected by the surface roughness but the variability decreases with the wind speed and the depth (see figure 2a). However, the pattern of the degree of polarization P decreases with wind speed (or MSS) and the depth (figure 2b); while unlike irradiance, the variability of P increases with wind speed and decreases with the depth.

(3) ***Effects of wave-induced light fluctuations on phytoplankton growth:*** Knowledge of the upper ocean light variability provides us a new possibility to model and explain the effects of light fluctuations on the surface phytoplankton growth characteristics which has been observed in the field. Using the analytical GP model we obtained, we showed that for surface phytoplankton exhibiting photo-inhibition features it is possible that under strong light illuminations such as in the summer their short-term (within one day) growth rate can decrease as the wind speed increases (figure 3a). An approximate linear dependence of growth rate and light variability at the upper ocean were also found (see figure 3b).

IMPACT/APPLICATIONS

The capability of accurate prediction of the irradiance transfer across ocean surface and in the water may enable the development of a novel approach for accurate measurements of complex ocean boundary layer processes and reliable detection of structures/objects on or above ocean surface based on sensed underwater irradiance data.

PUBLICATIONS

1. Shen, M., Z. Xu, and D. K. P. Yue (2011), A model for the probability density function of downwelling irradiance under ocean waves, *Opt. Express,* Vol. 19, No. 18, 17528-17538 [published, refereed].

2. Xu, Z., D. K. P. Yue, L. Shen, and K. J. Voss (2011), Patterns and statistics of in-water polarization under conditions of linear and nonlinear ocean surface waves, *J. Geophys. Res.,* 116 [published, refereed].

3. Xu, Z., X. Guo, L. Shen, and D. K. P. Yue (2012), Radiative transfer in ocean turbulence and its effect on underwater light field, *J. Geophys. Res.*, 117 [published, refereed]

STUDENTS GRADUATED

1 PhD (female), 1 Engineer (male)

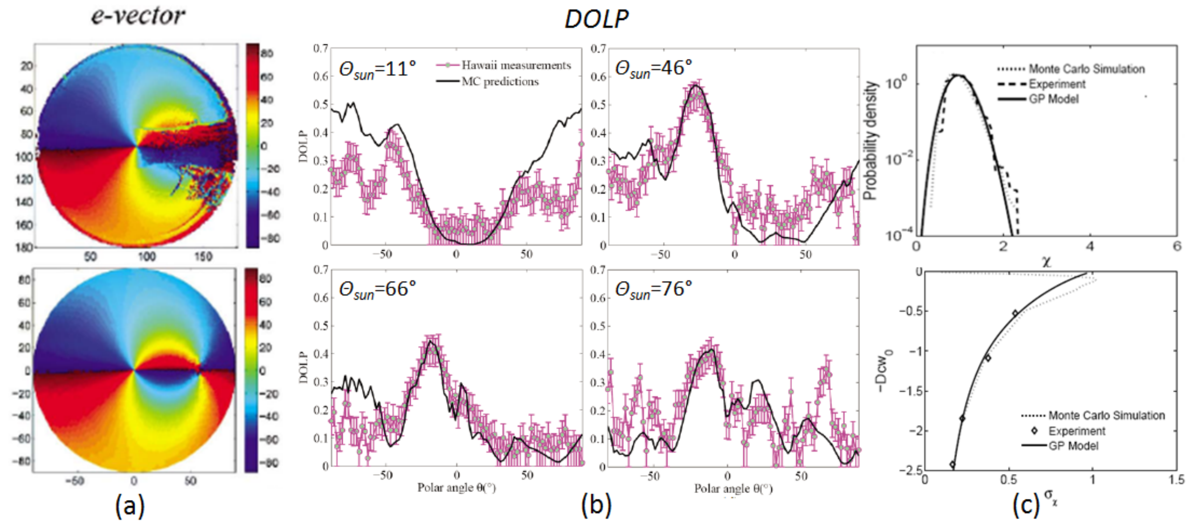

Figure 1. Validations of theoretical models by direct comparisons with experiments: (a) Comparisons of measured e-vector of sky polarized light fields (upper) with simulated result (lower); (b) Comparison of MC simulated in-water degree of linear polarization (DOLP) and measured in-water DOLP in Hawaii in the principal plane for different Sun's elevations; (c) Comparisons of PDF (upper) and variance of normalized downwelling irradiance χ= Ed/<Ed> between experiments, MC simulation and analytical GP model.

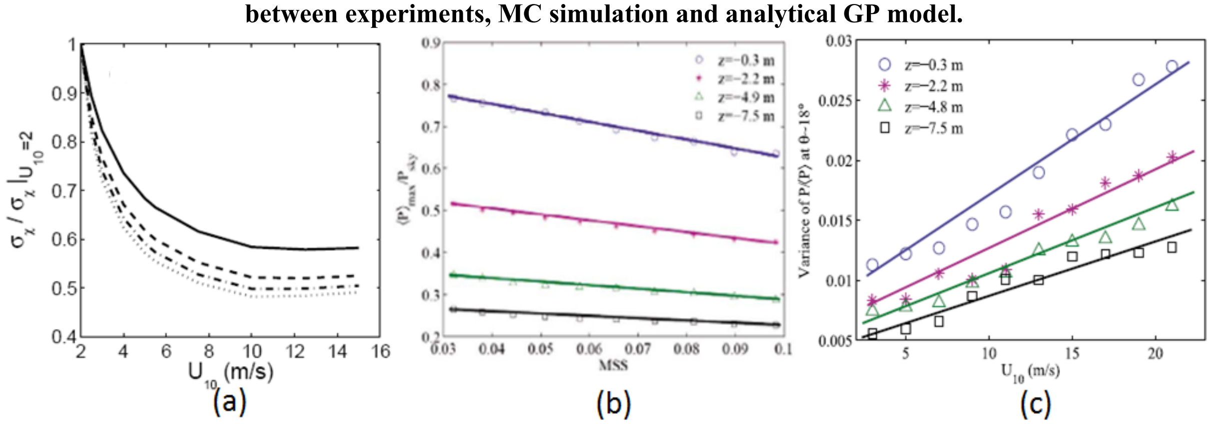

Figure 2. Dependence of unpolarized/polarized light pattern and variability on ocean surface roughness: (a) Variance of the normalized downwelling irradiance χ=Ed/<Ed> as a function of wind speed U_{10} for different depth z=-0.86m (—), -1.7m (- - -), -2.85m (- · -) and -4.72m (···). (b) Dependence of degree of polarization ratio $\langle P\rangle_{max}/P_{sky}$ on the mean square slope (MSS) of the ocean surface at different depth (z=-0.3, -2.2, -4.9 and -7.5 m). (c) Variance of the normalized degree of polarization P/<P> at the angular position of local maximum degree of polarization on the principal plane within the Snell's window as a function of wind speed U_{10} for four different depths.

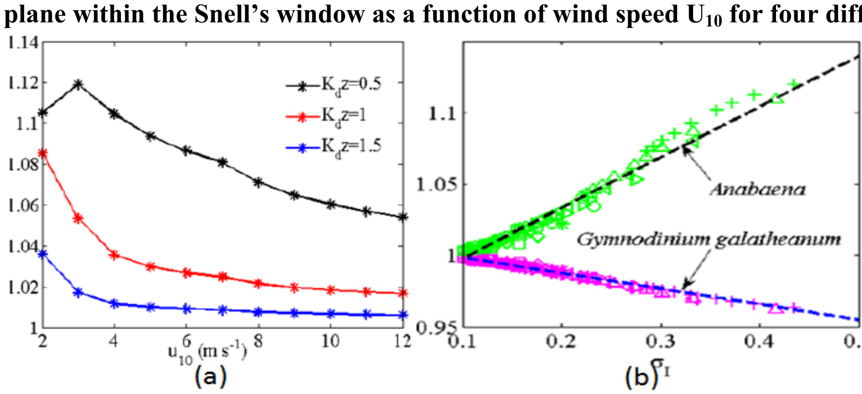

Figure 3. Effects of ocean wave roughness on surface phytoplankton growth rate: (a) Normalized daily growth rate γ versus wind speed u10 for *Anabaena* for summer at different optical depths. (b) Dependence of γ on scalar irradiance variability σI for *Gymnodinium galatheanum* (green symbols) and *Anabaena* (magenta symbols) for different optical depths K_dz=0.4 (+), 0.6 (Δ), 0.8 (◀), 1.0 (▶), 1.2 (O), 1.4 (*), 1.6 (◊) and 1.8 (□).